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Seismic Considerations¹

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13.1 Historical Perspective

Prior to 1970, seismic requirements for substation components were minimal. In the 1970s and 1980s, several large-magnitude earthquakes struck California, causing millions of dollars in damage to substation components and consequent losses of revenue. As a result of these losses, it became apparent to owners and operators of substation facilities in seismically active areas that the existing seismic requirements for substation components were inadequate. The 1997 version of the Institute of Electrical and Electronic Engineers (IEEE) Standard 693-1997, *Seismic Design for Substations* [1], and the document presently being produced by the American Society of Civil Engineers (ASCE), entitled *Substation Structure Design Guide* [2], have enhanced the current state of knowledge in this area. These documents also promote seismic standardization of substation power equipment in the electric power industry.

13.2 IEEE 693 — a Solution

The requirements necessary to qualify that substation power equipment can withstand seismic events were developed from research into seismic activity. No standard existed that provided a single set of requirements for seismic qualification of power equipment. The existing standard and guides provided methods for qualifying, but there was not a single set that, when met, would provide qualification. This is the main goal of IEEE 693: to provide a single set of requirements for each typical type of equipment that, when met, would provide qualification. Thus, the goal is that the manufacturer can include seismic requirements in the initial design of the equipment and amortize the cost of the qualification over all of the expected buyers.

This chapter discusses the current version of IEEE 693, released in 1997, and the changes in the next version of IEEE 693, scheduled to be published in 2004.

The relationship between seismic activity and substation equipment qualification is very complex and, because of the complexities, the IEEE 693 committee has attempted to simplify the application of the

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qualification process by organizing the information needed in the specification into four concise categories. These instructions will be discussed further, but briefly they are:

1. Note the equipment type, such as surge arresters or circuit breakers
2. Select the qualification level — low, moderate, or high
3. Note the equipment *in situ* configuration, such as mounting information, etc.
4. Identify scheduling requirements

The 2004 version will further simplify the process by providing a simple form to assist the user in specifying these requirements.

This chapter is intended to guide substation designers who have little familiarity with substation seismic design considerations by illustrating the basic steps required for securing and protecting components within a given substation. It is only a guide, and it is not intended to be all-inclusive or to provide all the necessary details to undertake such work. For further details and information on this topic, the reader should review the documents listed at the end of this chapter.

13.3 Relationship between Earthquakes and Substations

To secure and protect substation equipment from damage due to a seismic event, the relationship between earthquakes and substation components must first be understood. Earthquakes occur when there is a sudden rupture along a preexisting geologic fault. Shock waves that radiate from the fracture zone amplify, and depending on the geology, these waves will arrive at the surface as a complex set of multifrequency vibratory ground motions with horizontal and vertical components.

The response of structures and buildings to this ground motion depends on their construction, ductility, dynamic properties, and design. Lightly damped structures that have one or more natural modes of oscillation within the frequency band of the ground motion excitation can experience considerable movement, which can generate forces and deflections that the structures were not designed to accommodate. Mechanisms that absorb energy in a structure in response to its motion can help in damping these forces. If two or more structures or pieces of equipment are linked, they will interact with one another, thus producing a modified response. If they are either not linked, or linked in such a way that the two pieces can move independently — an ideal situation — then no forces are transferred between the two components. However, recent research has shown that even a well-designed link may contribute to the response of the equipment or structure during a seismic event.

For electrical reasons, most pieces of substation power equipment are interconnected and contain porcelain. Porcelain is a relatively brittle, low-strength, and low-damping material compared with steel. Furthermore, unless instructed to do otherwise, construction personnel will install conductors with little or no slack, which gives the installation a neat and clean look. This practice does not allow for any freedom of movement between components. When the conductor is installed with little or no slack, even small differential motions of one piece of equipment can easily impact an adjacent piece of equipment. This is because each piece of interconnected equipment has its own frequency response to an earthquake. While the equipment at one end of a tight conductor line is vibrating at 1 Hz, for example, the other piece of equipment at the other end of the conductor is “trying” to vibrate at, say, 10 Hz. It is easy to see that when they vibrate toward each other, the line will go slack. When they vibrate away from each other, the line will suddenly snap tight, which will impact the equipment. This is a well-documented occurrence. Usually, the larger, more massive equipment will pull the smaller, weaker equipment over. Substation equipment with natural frequencies within the range of earthquake ground motions are especially vulnerable to this type of damage by seismic events.

13.4 Applicable Documents

Once the relationship between substation components and earthquakes is understood, the substation designer should become familiar with the standards and references currently available (see reference list at the end of

this chapter). It is important for the user to appreciate how the various documents interrelate. Although the title of IEEE 693 is Recommended Practice for Seismic Design of Substations, it was clear to the IEEE 693 committee that other documents had already addressed many of the aspects of seismic design of substations. Therefore, IEEE 693 simply refers the users to the appropriate document if the information is not contained therein. It was also clear that a single set of seismic qualification requirements was needed; therefore the IEEE 693 emphasizes those aspects associated with the seismic qualification of power equipment.

Special attention also needs to be given to the ASCE's Substation Structure Design Guide. This guide provides information for all of the structures within a substation, such as A-frames, buildings, racks, etc. Since these two documents, IEEE 693 and the ASCE guide, were developed at about the same time, the two committees collaborated so that the two documents would complement each other. Simply stated, IEEE 693 addresses the equipment and its "first" support structure, while the ASCE guide addresses all the other structures.

13.5 Decision Process for Seismic Design Considerations

Once document familiarization is complete, the designer can follow the steps as outlined in [Figure 13.1](#), which was created with the assumption that each substation component will be reviewed independently.

The first step in the decision-making process is to determine whether the substation component under consideration is classified as power equipment or not. Assuming the component is classified as nonpower equipment, the next step is to determine what type of nonpower equipment the component is. For example, a structure such as a bus support may require foundation modification or anchor design work. Once the component type is determined, the appropriate references can be accessed and the required engineering work carried out. The decision-making process for substation components classified as nonpower equipment is then complete.

If the substation component under consideration is found to be a piece of power equipment, the next step in the power equipment decision process stream is to determine if this equipment is classified as Class 1E, equipment for nuclear power generating stations. IEEE 693 does not cover Class 1E equipment, but this information is available in IEEE 344 (1993) [3].

In the upcoming 2004 version, the next step of the power equipment stream will be to determine if this equipment's voltage class is less than 35,000 V. This is a new qualification classification that will be included in 2004. It is the "inherently acceptable" classification, meaning that this equipment has performed well in earthquakes without additional requirements. Most equipment less than 35 kV now falls in the category "inherently acceptable."

Certain types of equipment rated 15,000 V and less can be qualified using the experience-based qualification method as per Annex Q of IEEE 693. All other substation power equipment must be qualified as per the appropriate section in IEEE 693. It should be noted that IEEE 693 was written primarily for new installations, but it can be used to assist designers in the analysis of seismic requirements for existing equipment as well. Anchor design issues should be addressed as per the ASCE document and IEEE 693, as indicated in IEEE 693.

13.6 Performance Levels and Required Spectra

13.6.1 Background

Following the voltage classification, determination of the appropriate performance level for seismic qualification of the site in question must be selected. The performance level of earthquake motion is represented by response spectra that reasonably envelop response spectra from anticipated ground motions determined using earthquake records. The shape of the performance level is a broadband response spectrum that envelops the effects of earthquakes in different areas for site conditions ranging from soft soils to rock, as described in the National Earthquake Hazard Reduction Program (NEHRP) [4]. In 2004, the NEHRP maps will be replaced with the International Building Code (IBC) [5] maps.

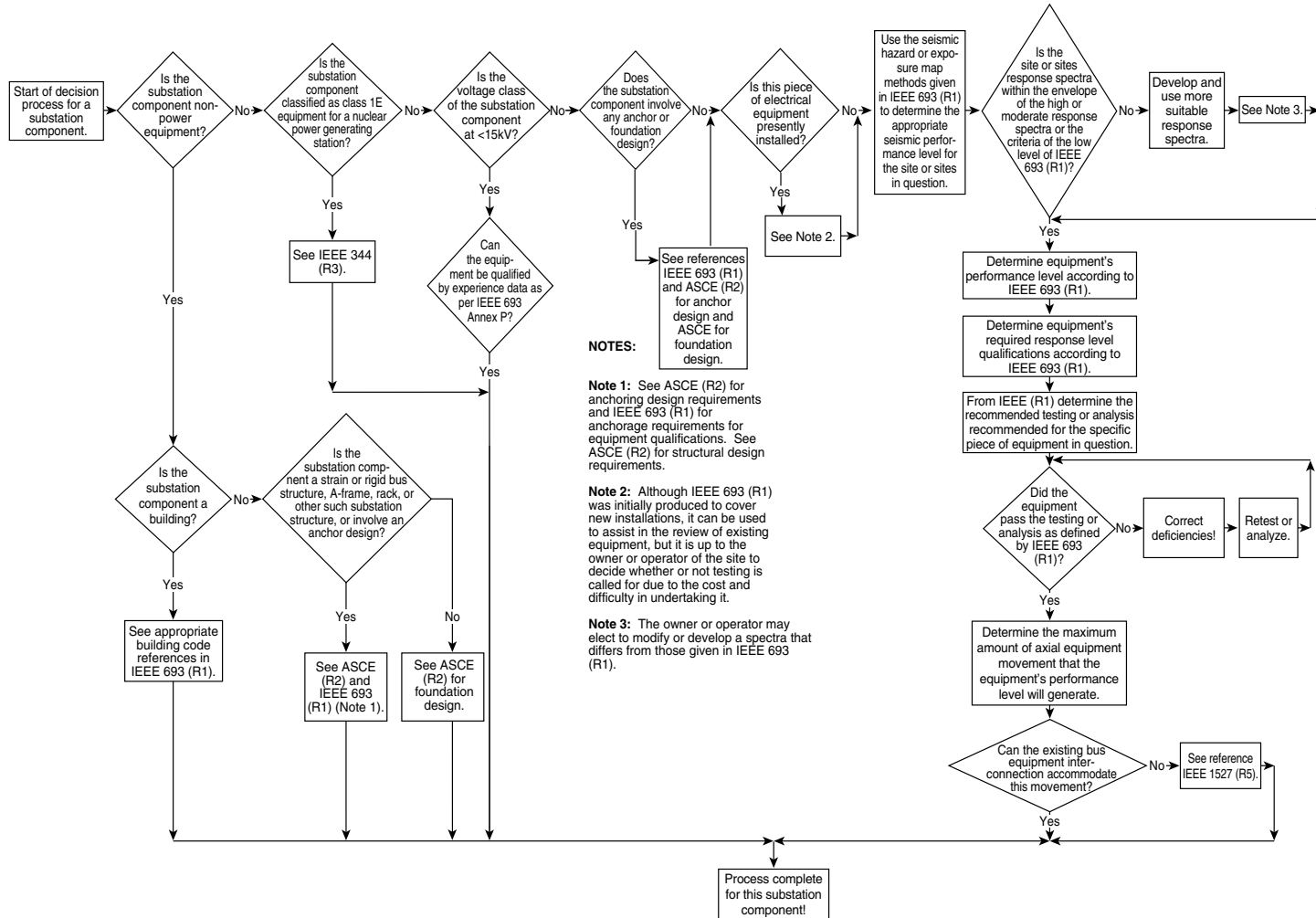


FIGURE 13.1 Decision process for seismic design considerations for substation components.

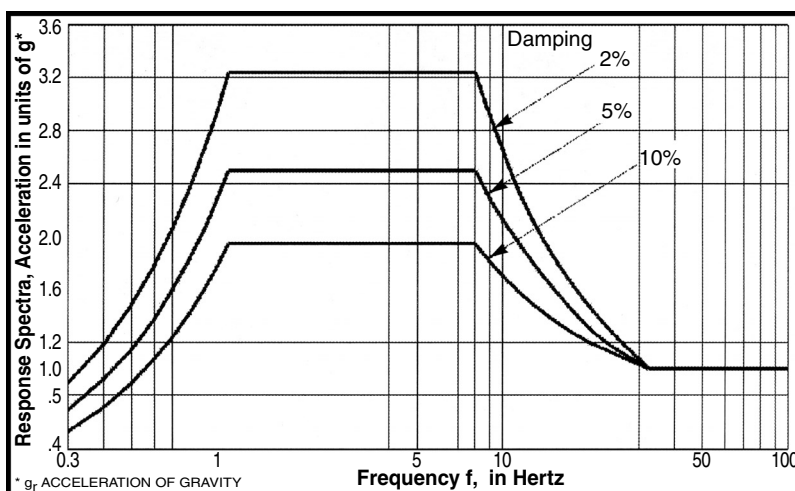


FIGURE 13.2 High seismic performance level (PL).

The performance level and the required response-spectrum shapes bracket the vast majority of substation site conditions. In particular, they provide longer period coverage for soft sites, but sites with very soft soils and sites located on moderate to steep slopes may not be adequately covered by these spectral shapes. Equipment that is shown by this practice to perform acceptably in ground shaking up to the “high seismic performance level” is said to be seismically qualified to the high level. In 2004, this statement will change to: “Equipment that is qualified in accordance with this practice to meet the objective with the ‘High’ Required Response Spectra (RRS) is said to be seismically qualified to the high seismic level.” The high seismic performance level is shown in Figure 13.2 with different damping percentages. In 2004, the high-performance-level figure will be removed from IEEE 693 because its application could be misinterpreted. Also, in 2004, the term “performance level” will be replaced with “projected performance level.” This new term better defines the relationship of the RRS and the acceptance criteria. A complete discussion of this issue is outside the scope of this chapter.

Equipment that has demonstrated acceptable performance during a “moderate” event is said to be seismically qualified to the moderate level. In 2004, this statement will change to: “Equipment that is qualified in accordance with this practice to meet the objective with the ‘Moderate’ RRS is said to be seismically qualified to the moderate seismic level.” The moderate seismic performance level is shown in Figure 13.3 with different damping percentages. In 2004, the moderate-performance-level figure will also be removed from IEEE 693.

Finally, equipment that has demonstrated acceptable performance during a “low” event is said to be seismically qualified to the low level. In 2004, this statement will change to: “Equipment that is qualified in accordance with this practice to meet the objective with the ‘Low’ seismic criteria is said to be seismically qualified to the low seismic level.” The low seismic performance level represents the performance that can be expected when good construction practices are used and no special consideration is given to seismic performance. In general, it is expected that the majority of equipment will have acceptable performance at 0.1 g or less. The performance level for a site is determined by using either an earthquake hazard map or seismic exposure map for the appropriate part of North America, as specified in IEEE 693. For example, in the U.S., the procedure to select the appropriate seismic qualification level for a site using the earthquake-hazard-map method consists of the following steps:

1. Establish the probabilistic earthquake hazard exposure of the site where the equipment will be placed. Use the site-specific peak ground acceleration developed in a study of the site’s seismic hazard, selected at a 2% probability of exceedance in 50 years, modified for site soil conditions.

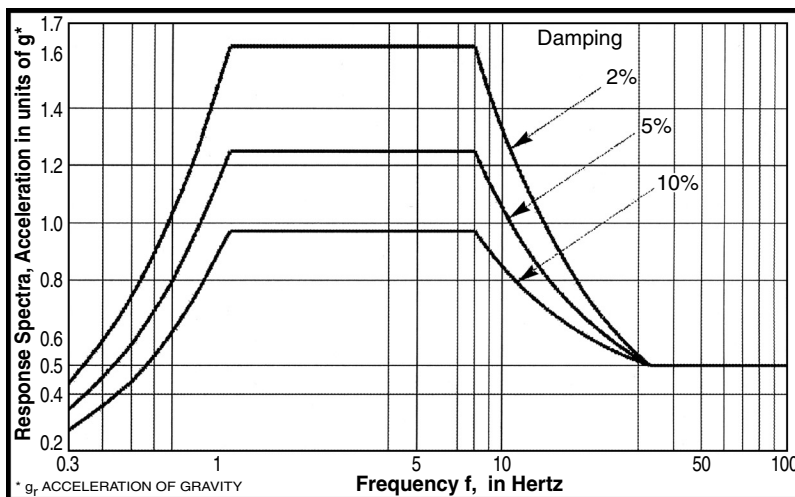


FIGURE 13.3 Moderate seismic performance level (PL).

2. Compare the resulting site-specific peak acceleration value and spectral acceleration with the three seismic performance levels — high, moderate, or low — that best accommodates the expected ground motions. If the peak ground acceleration is less than or equal to 0.1 g, the site is classified as low. If the peak ground acceleration is greater than 0.1 g but less than or equal to 0.5 g, the site is classified as moderate. If the peak ground acceleration is greater than 0.5 g, the site is classified as high. This level then specifies the seismic qualification level used for procurement.

When selecting the qualification level based on performance levels, it should be remembered that performance levels represent levels of ruggedness based on testing at lower levels combined with factors of safety for material, or based on analysis combined with experience from previous earthquakes. These performance levels therefore have an inherent degree of uncertainty. For better assurance of structural performance during an earthquake, owners or operators may require that the qualification spectra be increased from low to moderate or from moderate to high to better fit the equipment performance level that they desire. The owners or operators should carefully weigh the benefits of deviating from the criteria specified herein against the added costs.

The earthquake-hazard method is the preferred approach and can be used at any site, but the seismic-exposure-map method can be undertaken utilizing the NEHRP-1997 maps in the U.S. In 2004, the International Building Code (IBC) ground-motion maps can be used in the U.S. The 1995 National Building Code of Canada (NBCC) maps should be used for Canada. The Manual de Diseno de Obras/ de la Comision Federal de Electricidad (MDOC/CFE) maps should be used in Mexico. Other countries should use equivalent country-related maps.

To select the appropriate seismic qualification level for a particular service area using the NEHRP maps, the steps outlined below should be followed:

1. Determine the soil classification of the site (A, B, C, D, or E) from section 1615.1.1.
2. Locate the site on the maps (section 1615.1) for the Maximum Considered Earthquake Ground Motion 0.2-sec Spectral Response Acceleration (5% of critical damping).
3. Estimate the site 0.2-sec spectral acceleration, “ S_s ,” from this map.
4. Determine the value of the site “ F_a ” from Table 1615.1.2(1), as a function of site class and mapped spectral response acceleration at short periods (S_s).
5. Use the peak ground acceleration to select the seismic qualification level. If the peak ground acceleration is less than or equal to 0.1 g, the low qualification level should be used. If the peak

is greater than 0.1 g but less than or equal to 0.5 g, the moderate qualification level should be used. If the peak is greater than 0.5 g, the high qualification level should be used. Use of one of the three qualification levels given in this guideline (IEEE 693) and the corresponding required response spectra is encouraged. Use of different utility-specific criteria will likely lead to higher cost and will not meet the intent of this guideline with regard to uniformity.

Similar methods for evaluating seismic qualification methods used in Canada and Mexico are also given in IEEE 693, with appropriate country-specific references and maps as required. Other countries can use a method similar to those described in IEEE 693. Judgment and experience must be exercised when selecting the performance level for seismic qualification, as the site hazard may not fall directly on the high, moderate, or low seismic performance level. In this case, a strategy on accepting more or less risk will be required. It is recommended that large blocks of service areas be dedicated to a single performance level to increase postevent performance consistency and interchangeability and to help reduce costs through bulk purchases. For existing facilities it will mean increased efficiency in any upgrade or repair design work that may be required. Additional operational requirements must also be considered when selecting equipment for an active inventory of an operating utility. The owner/operator must therefore evaluate all of the sites in the service territory and establish a master plan, designating the required (or desired, as the case may be) performance level of each site and prioritizing those sites that need to be upgraded to meet current standards. Likewise, after a site for new electrical equipment has been identified, the owner or operator's agent must determine the appropriate seismic performance level.

If the seismic response spectra for a specific site falls significantly outside of the response spectra indicated in [Figure 13.2](#) and [Figure 13.3](#), then a more appropriate response spectra will have to be developed for use by the owner or operator at that specific site. If the new response spectra falls outside the ones defined in IEEE 693, then the basic procedure laid out in the rest of the decision-making process of Figure 5.80 in IEEE 693 can still be followed. However, the high, moderate, and low levels specified in IEEE 693 should be used without deviation unless it is very clear that one of the performance levels will not adequately represent the site or sites. Note that if the owner or operator elects to modify or develop a spectra that differs from those given, the user will lose the benefits of the standardization. In 2004, the document will specifically state that the user and manufacturer will lose the right to state that the equipment is qualified according to IEEE 693, should the requirements be reduced.

It is often not practical or cost effective to test to the high or moderate performance level because:

1. Test laboratories may not be able to attain these acceleration levels, especially at low frequencies.
2. More importantly, the yield strength of the in-service ductile materials may be considered acceptable at the performance level, and testing to a higher performance level could lead to damage of components, resulting in an unnecessary financial loss.

For these reasons, the equipment should be tested at 50% of the required performance level. For consistency, analysis will also be performed at 50% of the performance level. This reduced level is called the RRS. For the high level, compare [Figure 13.2](#) with [Figure 13.4](#), and for the moderate level, compare [Figure 13.3](#) with [Figure 13.5](#).

The ratio of performance level (PL) to required response spectra (RRS) in this practice is 2.0. This factor is called the performance factor (PF), i.e., the performance factor is $PF = PL/RRS$. The performance factor does not apply to the low seismic level.

Equipment that is tested or analyzed to the required response spectra is expected to perform acceptably at that performance level. This is achieved by measuring the stresses in the components obtained from the test or from the analysis at the required response spectra and by applying the acceptance requirements list in IEEE 693. For uniformity, in 2004 the "performance level" is being changed to "projected performance level," and the "performance factor" is being changed to the "projected performance factor."

Theoretically, for the reasons stated, components qualified using the moderate or high RRS should be able to withstand ground shaking at the respective performance level. It is cautioned that this approach is dependent upon identifying the locations with the highest stresses within an individual piece of

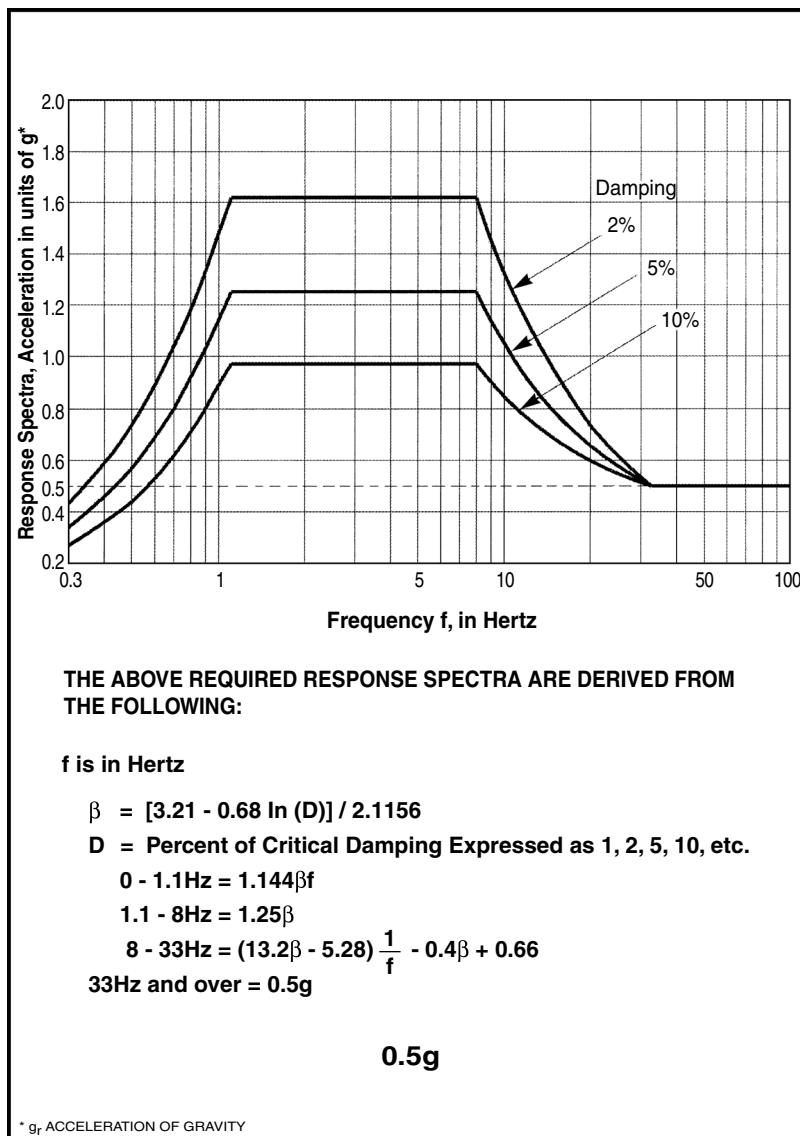


FIGURE 13.4 High required response spectrum (RRS).

equipment, and then monitoring the stresses at these locations during testing or analysis. If the testing or analysis is not carried out in this manner, the critical locations within the equipment may fail prematurely during a seismic event. In addition to these considerations, the response of the equipment to the dynamic load may change between the required response spectra and the performance level. If this is not anticipated, premature failures may occur.

The above discussion pertains to the structural performance of the equipment. Qualification by analysis provides no assurance of electrical function. Shake-table testing provides assurance for only those electrical functions verified by electrical testing and only to the required response spectra level, not to the performance level. Shake-table testing may be required for equipment that in previous years was qualified by dynamic analysis but performed poorly during past earthquakes. However, static or static-coefficient analysis may still be specified when past seismic performance of equipment qualified by such methods has led to acceptable performance.

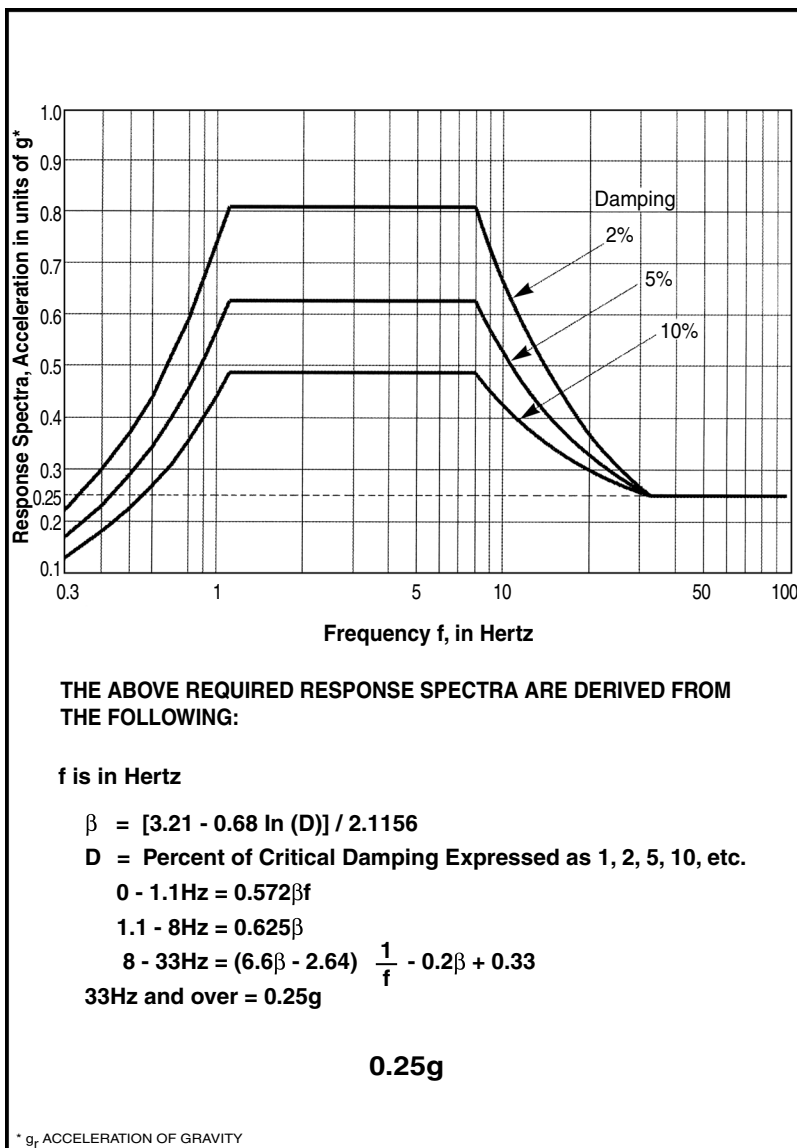


FIGURE 13.5 Moderate required response spectrum (RRS).

13.6.2 High and Moderate Levels

The high and moderate required response spectra are given in Figure 13.4 and Figure 13.5, respectively. The required spectral shape for the response spectra is the same as that used in the performance, except at 50% of the performance level. The equations for the respective spectra are listed in Figure 13.4 and Figure 13.5.

13.6.3 Low Level

A rigorous seismic qualification, such as that required to meet the high and moderate performance levels, is not required for equipment qualified to the low performance level. That is, no required response spectrum or seismic report is required. However, the following criteria should be met:

1. Anchorage for the low seismic performance level shall be capable of withstanding at least 0.2 times the equipment weight applied in one horizontal direction, combined with 0.16 times the weight applied in the vertical direction at the center of gravity of the equipment and support. The resultant load should be combined with the maximum normal operating load and dead load to develop the greatest stress on the anchorage. The anchorage should be designed using the requirements specified in IEEE 693 and the ASCE guide.
2. The equipment and its support structure should have a well-defined load path. The determination of the load path should be established so that it describes the transfer of loads generated by, or transmitted to, the equipment from the point of origin of the load to the anchorage of the supplied equipment. Among the forces that should be considered are seismic (simultaneous triaxial loading — two horizontal and one vertical), gravitational, and normal operating loads. The load path should not include:
 - Sacrificial collapse members
 - Materials that will undergo nonelastic deformations, unrestrained translation, or rotational degrees of freedom
 - Solely friction-dependent restraint (control-energy-dissipating devices excepted)

13.7 Qualification Process

Once the performance level has been established, the testing or analysis as required in the IEEE 693 document must be undertaken. For example, to qualify a 138,000-V circuit breaker to meet the moderate seismic qualification level, the following criteria, as specified in IEEE 693, must be successfully demonstrated:

1. The seismic-withstand capability must be demonstrated by performing a dynamic analysis, and the analyzed equipment should include the control cabinet, stored energy sources, and the associated current transformer, assuming this equipment is on the same support structure.
2. The circuit breaker and the supporting structure must be designed so that there will be no damage during and following the seismic event.
3. The response spectrum shown in [Figure 13.5](#) should be used in the analysis.

The IEEE 693 document also provides guidance on the following for this piece of equipment:

1. General requirements for dynamic analysis
2. General and detailed qualification procedures required
3. Criteria for establishing when the qualification is considered acceptable
4. Equipment and support design
5. A report analysis checklist
6. Information on how to include base isolation and other damping systems in the analysis
7. Recommendations on what seismic information should be listed on the equipment identification plate

This IEEE 693 document also contains similar material for nearly all other substation components.

Because of the way IEEE 693 is written, the information that the users must provide in their tendering specifications is minimal. A few paragraphs are usually all that are necessary, as the controlling language is contained in IEEE 693. Therefore, it is strongly suggested that rather than copying information from the IEEE 693 document into the user's specifications, that the user refer to the document in its entirety. This eliminates the possibility of a misunderstanding between the owner and the manufacturer. Also, if the document is not specified in its entirety, then the user and manufacturer should not claim that the equipment is in compliance with IEEE 693.

Based on the results of the testing and analysis undertaken, corrective measures can be carried out to seismically upgrade the power equipment in question. The maximum amount of equipment displacement is also determined from these tests or from dynamic analysis.

The final step of the decision process for the power equipment stream is to determine the flexible bus interconnection required for the piece of equipment. IEEE 693 provides guidance in determining the minimum length of flexible bus, while IEEE 1527 [6], which is still in a draft form, will provide a more detailed design procedure to follow. The basic decision-making process for substation components that are classified as power equipment is now complete.

References

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2. American Society of Civil Engineers, Substation Structure Design Guide, ASCE, Reston, VA, 2004.
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